Applied Clay Science 153 (2018) 16–22

Contents lists available at ScienceDirect

Applied Clay Science

journal homepage: www.elsevier.com/locate/clay

Research paper

Effects of calcium concentration and differential settlement on permeability characteristics of bentonite-sand mixtures

Sifa Xu, Mengdan Bian, Cuifeng Li, Xuehui Wu, Zhe Wang*

School of Civil Engineering and Architecture, Zhejiang University of Technology, Hangzhou 310014, PR China

A R T I C L E I N F O

Keywords:
Bentonite-sand mixtures
Differential settlement
Deflection
Crack
Ca^{2+}
Permeability

A B S T R A C T

Liner systems consisting of clay or bentonite-sand mixtures can be installed on the bottom of landfills to prevent contaminants from seeping into the surroundings. Differential settlement of the foundation and presence of heavy metal or alkali metal ions in the leachate can vastly affect permeability characteristics of the liner system. In this study laboratory model tests were performed to investigate the influence of differential settlement and Ca^{2+} on permeability characteristics of bentonite-sand mixtures. The results showed that when the thickness of bentonite-sand mixtures was 100 and 200 mm, cracks were formed within the bentonite-sand mixtures with respective deflections of 2.5 and 7.0 mm. When the height of developed cracks exceeded 50% and 70% of the thickness, the permeability characteristics of bentonite-sand mixtures was > 10^{-7} cm/s. Ca^{2+} concentration has great impact on the permeability characteristics of bentonite-sand mixtures. Na-bentonite will be converted to Ca-bentonite when the concentration of Ca^{2+} is two times greater than that of Na^{+} in the solution, and the anti-seepage performance of bentonite-sand mixtures will consequently deteriorate.

1. Introduction

In order to protect underlying ground-water resources from pollutants, both the bottom and closure cap of landfills are lined with infiltration proof layers. Compacted clay or bentonite-sand mixtures are widely used materials for liner systems. Generally, landfill liners require compacted clay or bentonite-sand mixtures with permeability coefficient (k) ≤ 10^{-7} cm/s (CJ113–2007, 2007; US EPA, 2012).

Problems may arise if the foundation of landfills located in karst terrain is not handled properly (Chen et al., 2008), or when pipelines for groundwater collection are in soft soil or soil not compacted adequately. Differential settlement of landfill foundation may occur due to the weight of garbage or compaction efforts by machinery, which in turn leads to bending deformation of the infiltration proof layer (Albrecht and Benson, 2001). Crack resistance of the clay and bentonite-sand mixtures is very poor (Chen et al., 2014). A slight bending deformation will produce cracks, which thus adversely affect the permeability (Gourc et al., 2010), intensifies migration of pollutants into the ground, and result in major engineering and environmental disasters. Therefore, it is of great significance to study the deformation, cracks, and permeability characteristics of the clay and bentonite-sand mixtures.

Clay and bentonite-sand mixtures have specific properties under tension. Experiments have been carried out to study the development of tensile cracks due to differential settlement. The commonly employed methods are uniaxial tensile test, triaxial extension test, soil beam bending test, and splitting test. Through uniaxial tensile tests on compacted clay, Zhang et al. (2013) studied bending deformation characteristics of clay, and analyzed the effect of compaction degree of clay on its tensile stress-strain curves. In reference to research on basic mechanical characteristics of clay, some studies used soil beam bending test to examine the relationship between bending deformation and cracking of clay beam. Gourc et al. (2010) found that when the distortion reached 2–3%, 1 or 2 main crack zones developed in the upper part of the soil beam, with the average width of crack reaching 7 to 15 cm. There are also researches that measure the strain of the soil by setting markers on the surface of the soil, or employing the four point bending test of clay beam. These results showed that the cracking strain was about 0.001 to 0.02, and the corresponding distortion was between 0.01 and 0.03. (Viswanadham et al., 2009; Camp et al., 2010). Centrifuge model test and field test were also used to explore the deformation characteristics of clay liner under differential settlement of underlying soil. These findings indicated that clay layer would crack or collapse with no overburden pressure (Jessberger and Kockel, 1993). A numerical simulation was carried out by Plé et al. (2012) to interpret data from both laboratory and field tests. This simulation was then used to study the crack formation in the clay cover barrier caused by differential settlement and predict the initiation cracks. Ling et al. (2015)

* Corresponding author.
E-mail addresses: xusifa@zjut.edu.cn (S. Xu), wangzsd@zjut.edu.cn (Z. Wang).

https://doi.org/10.1016/j.clay.2017.11.029
Received 21 July 2017; Received in revised form 20 November 2017; Accepted 21 November 2017
Available online 06 December 2017
0169-1317/

studied the cracking characteristics of compacted clay beams with different moisture contents and investigated the process of crack propagation. Strain localization near the crack tip was found, and cracking strain of compacted soil beams with different moisture contents was obtained, utilizing three point bending tests of compacted clay beams. Cai et al. (2014) studied the tension cracking process of clay and the effect of moisture content on the cracking behavior. A simplified saturated/unsaturated seepage model of the barrier with a single crack was proposed to investigate the process of preferential flow. They found that the location of cracks initiation could greatly influence the seepage prevention capability of compacted clay layer.

Cracks in clay or bentonite-sand mixtures can adversely affect the integrity of the infiltration proof layer by becoming channels of leachate and gases, and as a result reducing its anti-seepage capability. Because of the difficulty in measuring permeability of cracks and observing the development and distribution of cracks after construction of the liner, it is hard to quantitatively evaluate the effect of cracks on the seepage prevention ability of compacted clay layer. At present, assessment is mainly through field monitoring, testing, and excavation. Melchior et al. (2010) conducted field monitoring of compacted clay landfill cover systems for ten years. The integrity of compacted clay layer was examined by excavation at several positions throughout the years. Results revealed that cracks formation due to desiccation, plant root penetration, and other factors may have a significant impact on the seepage prevention capacity of the clay layer. Sadek et al. (2007) assessed the effect of desiccation cracks, induced by drying and wetting cycles, on anti-seepage performance of clay barrier layer. Varying parameters such as saturated permeability characteristics and soil-water characteristic curve, simulations of both intact and cracked clay covers were performed to examine how cracks affect water infiltration into the landfill. After continuous monitoring the water balance of a compacted clay barrier layer for 864 days, Albright et al. (2006) found that the existence of cracks could increase the permeability characteristics of the clay layer by approximately three orders of magnitude. Dwyer (2003) evaluated the infiltration through landfill covers using water balance computer programs. But those programs failed to yield desirable accuracy when compared to field data. Some scholars have proposed mathematical models including preferential flow paths in soil with cracks, such as single-porosity models (Ross and Smettem, 2000) and dual-porosity models (Genuchten, 1980; Gerke and Van Genuchten, 1993). But there is still a significant difference between the calculations and actual results.

Large amount of waste or waste incineration ashes are routinely transported to be disposed at landfills. Besides a variety of heavy metals, there are a lot of alkali and alkaline earth metal oxides (Na, K, Ca, and, Mg) in the leachate (Li et al., 2008), and the concentration of CaO can be very high (Wang et al., 2009). The pH of leachate could reach 12.5, even higher than the alkalinity of saturated $Ca(OH)_2$ solution (Quina et al., 2008). Calcium ions are abundant in municipal solid wastes, and once the leachate with Ca^{2+} flows into the sodium bentonite-sand mixtures, it may severely change the permeability of the mixed soil layer.One study showed that the swelling pressure of bentonite decreased with the increase of pH, and the extent of decrease was temperature dependent (Ye et al., 2014). Experimental results also indicated that the free expansion and swelling of bentonite decreased and the permeability characteristics gradually increased with higher cation valence and concentration (Xu et al., 2009; Sun et al., 2015).

As mentioned above, existing researches mainly focus on tensile strength and crack characteristics of soil. However, there is no adequate investigation on development of cracks in soil regarding the change of deflection, change of permeability during crack development, and effect of Ca^{2+} concentration on permeability of bentonite-sand mixtures. In this study, laboratory scaled model experiments were conducted to study several aspects of bentonite-sand mixtures: deformation characteristics under differential settlement, correlation between cracks and permeability characteristics of mixtures layer, and effect of the Ca^{2+} concentration on the permeability characteristics.

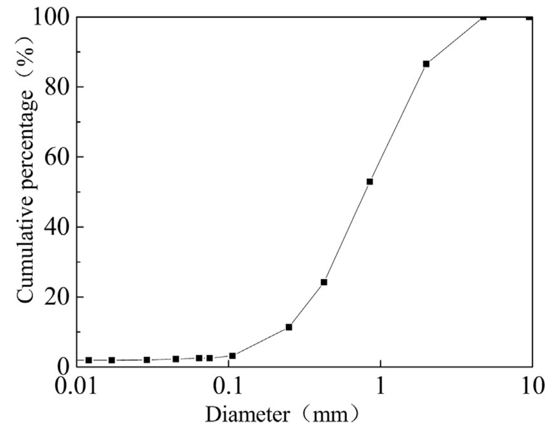

Fig. 1. Particle-size distribution of sand.

2. Materials and methods

2.1. Materials

The particle-size distribution of the sand used was obtained by dry sieving method and is presented in Fig. 1. The sand is well sorted with a mean grain diameter D50 of 0.8 mm, and the maximum particle size is < 5 mm. The portion of fine particles is 2.52%. The uneven coefficient is 5.1 and the curvature coefficient is 1.15. All parameters indicate that the sand used belongs to the good soil gradation. The bentonite studied is sodium bentonite, chemical and X-ray diffraction (XRD) tests indicated that the bentonite contains montmorillonite (78.5%), quartz (12.3%), feldspar (5.6%), calcite (2.2%) and organic carbon (0.8%). Its specific gravity is 2.76, and the cation exchange capacity is 0.77 $meqg^{-1}$. The concentration of Na^{+} is 0.41 mmol/g and the concentration of Ca^{2+} is 0.28 mmol/g.

Results of Proctor compaction tests (compaction energy = 592.2 kJ/m^3) on sand and bentonite-sand mixtures are shown in Fig. 2. The Proctor compaction curve shows that the optimal dry density of sand is 1.64 g/cm^3 with an optimal moisture content of 12.5%. With 10% (kg/kg, dry basis) bentonite in the bentonite-sand mixtures, the optimal dry density is 1.67 g/cm^3 with an optimal moisture content of 17.4%.

Fig. 3 shows the relationship between infiltration time and permeability characteristics at 95% compaction. The permeability characteristics is 5.5×10^{-8} cm/s at steady state by penetration test, which meets the requirement of landfill as impervious material.

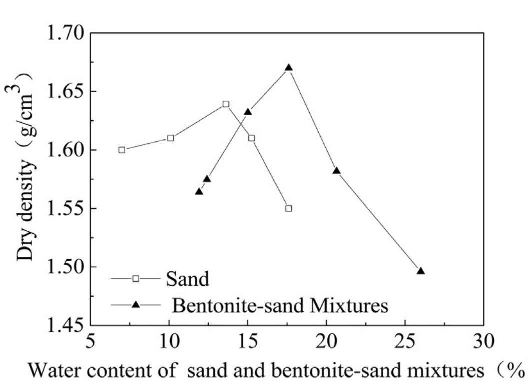

Fig. 2. Compaction curves.